23rd CIRP Conference on Life Cycle Engineering

Scenario Design Approach to Envisioning Sustainable Manufacturing Industries to 2050

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Abstract

There is an increasing need for the manufacturing industry to achieve environmental sustainability. Scenario design is a promising approach to delineating multiple visions of sustainable manufacturing industries (SMIs). This paper aims to discuss advantages and challenges of a scenario design approach for achieving SMIs. To this end, we review existing scenarios and methods associated with SMIs. Using a backcasting scenario design method, we carry out a case study of Japan’s SMI to 2050 in order to examine the potential of scenario design. The results reveal that computer-aided scenario design is helpful for clarifying the logical structure and rationales of the scenarios.

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Peer-review under responsibility of the scientific committee of the 23rd CIRP Conference on Life Cycle Engineering

Keywords: sustainable manufacturing industry; scenario design, backcasting

1. Introduction

The manufacturing industry is faced with an unavoidable challenge to achieve environmental sustainability, such as climate change and minerals resource scarcity. Research on sustainability for the manufacturing industry has been progressed accordingly. From a technological viewpoint, the world is witnessing emerging technology elements that would be helpful to realize a sustainable manufacturing industry (SMI), such as additive manufacturing and renewable energy. From a business model viewpoint, various concepts have been proposed, such as Industrie 4.0 [1], Industrial Internet of Things (IIoT) [2], life cycle design [3], and industrial product service systems (IPS)\(^3\) [4]. However, when we attempt to design a sustainable manufacturing industry in a particular context (e.g., region and time frame), one critical obstacle is a variety of uncertainties associated with future manufacturing industries, such as global economic situations, resource availability, and people’s lifestyles. While the CIRP community has enthusiastically been committed to research on developing SMI (e.g., [5][6]), the influence of time axes on the manufacturing industry has not sufficiently been examined.

The key questions here include (i) what visions of SMIs in the future should be crafted and (ii) how those visions and the present should be bridged. Scenario design is a promising approach to answer these questions. This paper discusses the advantages and research challenges of scenario design toward SMIs. To this end, we review existing scenarios of manufacturing industries and scenario design methods. To help design scenarios, we introduce methods for computer-aided scenario design. In a case study, a scenario exercise of Japan’s SMI to 2050 is presented using backcasting.

2. Literature review of scenarios and scenario design methods related to SMIs

2.1. Scenarios

According to our comprehensive literature review [7], a number of researchers and research organizations have been actively engaged in scenario studies in the context of sustainability since 1990s. Here, scenarios are not a prediction, but aim at explicitly describing alternative futures that might happen, thereby helping generate possible policies and actions

doi:10.1016/j.procir.2016.04.103
to be taken in those futures [8]. Scenarios can typically be categorized into two types – forecasting and backcasting. As depicted in Fig. 1, forecasting scenarios define the present as the starting point for drawing futures, while backcasting scenarios explore paths backward from predetermined future visions to the present in order to discuss what is necessary to arrive at the envisioned future visions [9]. A backcasting scenario is represented as the combination of a vision of and pathways to desirable (or undesirable) futures. Backcasting is considered suitable for addressing long-term problems that require drastic changes, such as establishing a sustainable society [10].

The IPCC’s Emissions Scenarios is one of the most famous forecasting scenarios, which described several storylines to analyze the impact of greenhouse gas emissions on global warming [11]. Energy Technology Perspectives is an example of backcasting scenarios, which examined the feasibility of achieving a low-carbon society with a variety of energy technologies [12].

In the context of SMIs, several scenarios have been published in the last decade by research organizations and governments, often in European countries. Geyer et al. [13] presented four socio-economic scenarios of future manufacturing in Europe from 2015-2020. The assumed scenarios varied depending on the modality of policies and prevailing values & behaviors, upon which strategies to be taken by the European manufacturing industry were discussed. European Commission [14], in turn, described four scenarios in possible strategies that the manufacturing industry might take. The scenarios analyzed the strengths and weaknesses of the assumed strategies, which differed in, for example, production systems (centralized versus distributed) and manufactured products (high quality versus innovative). The UK government [15] described three scenarios of the UK manufacturing to 2035. The aim was to assess the long-term impact (mainly in GDP) of emerging economies on the UK manufacturing.

2.2. Scenario design methods

Along with an increasing need for scenarios, much effort has been made in developing methods for designing scenarios [7]. Scenario planning is regarded as the most popular method to build scenarios in a business context [16]. It often applies the two-axis method (which is sometimes preferred by business schools) to generate four contrasting scenarios, where two key drivers as “high impact, high uncertainty” factors are chosen. In order to develop business strategies, Gausemeier et al. [17] presented a scenario creation process based on systems thinking and multiple futures. Although a variety of methods have been developed in the domain of scenario planning, the common idea here is to explore effective business strategies for enterprises by assuming multiple future business environments.

While scenario planning tends to use forecasting scenarios as a whole, the idea of backcasting is becoming more important in designing scenarios for sustainability [18]. Robinson [9] proposed a generalized procedure to develop backcasting scenarios. It consists of 6 steps, beginning with determining the purpose of scenario building and ending with undertaking impact analysis. With stakeholder participation, the process of designing backcasting scenarios involves developing a single or multiple visions and pathways to reach those visions [7]. Obviously, visions of sustainable futures are of normative nature and depend on many factors, such as stakeholders’ views, cultures, and available technologies. Therefore, participatory backcasting aims at reflecting different views and knowledge regarding sustainability on backcasting scenarios. To this end, workshops are often used in the participatory backcasting process by involving experts from different disciplines as well as stakeholders. A participatory approach, including participatory backcasting, leads to sharing various knowledge and ideas, enhancing mutual learning among the participants, and co-creating new knowledge toward sustainable futures [7][18].

2.3. Problems

Looking at long-term futures such as 2050, the manufacturing industry will be faced with several critical constraints. They include, at least, global population growth, economic growth, climate change, and resource depletion, as mentioned by Rahimifard et al. [19]. With regard to climate change, the IPCC’s greenhouse gas emissions scenarios [11] described temperature projections to 2100 with a rise of 0.3-4.8 degrees Celsius from the 1990 level in spite of mitigation policies. From the viewpoint of resource depletion, the authors [20] estimated copper demand in the world to 2050 based on the assumptions of the existing energy scenarios by International Energy Agency (IEA) [12]. The results showed that the estimated copper demand would exceed the reserve base by 2040 due mainly to a demand rise in emerging countries. In addition, energy issues must be considered as energy transformation attracts much attention worldwide after the Fukushima nuclear power plant accident in the aftermath of the Great East Japan Earthquake in 2011.

In attempting to devise scenarios of SMI, manufacturing industries must take into account such constraints as shown above. However, existing scenarios partly listed in Section 2.1 have not yet covered a holistic view of SMI. From a methodological viewpoint, there are few systematized ways as
to how scenarios of SMI should be designed in a way that answers the research questions (i) and (ii) in Section 1.

3. Methods for computer-aided scenario design

3.1. Sustainable Society Scenario (3S) Simulator

With the aim of providing a systematized method in designing scenarios using a participatory approach, we have been proposing methods for computer-aided scenario design mainly in CIRP journals and CIRP conferences [21]-[24]. Implementing the proposed methods, we have developed a computer-aided (scenario) design system, called “Sustainable Society Scenario (3S) Simulator” [21]. The system helps the scenario designers to compose and analyze scenarios with the involvement of various stakeholders (e.g., researchers, policymakers, and citizens). One characteristic of the system is to represent a scenario as a network graph (i.e., nodes and links) in order to clarify the logical structure. This clarification helps the scenario designers to have a common understanding on the underlying assumptions, ideas and views of the scenario with different stakeholders. Another characteristic is to accumulate existing scenarios and simulators, helping to design new scenarios.

3.2. Method for designing backcasting scenarios

While 3S Simulator is equipped with the functions to support the design of both forecasting scenarios and backcasting scenarios, this section introduces a method for designing backcasting scenarios, which is used in the case study (see Section 4). In this method, we modeled a sub-scenario as the combination of a vision and one of its transition paths (Fig. 1). In general, several sub-scenarios are described to explore different visions of sustainable futures and different pathways to reach one of the visions.

Difficulties in describing backcasting scenarios include how to craft visions of sustainable futures and how to support backward thinking in describing transition paths connecting to the visions from the present. Our approach was to employ logic trees to assist the scenario designers in allowing backward thinking from visions to achieve to means required to arrive at each of the visions [25]. Fig. 2 shows an example as to how we use logic trees to support backward thinking by connecting a vision (represented as “target” node) with factors required to achieve the vision (represented as “factor” node). Of all factors, we choose several key factors as the most influential factors on the vision in order to delineate different scenarios by deploying from each key factor.

We defined the process to describe the scenario in the following four steps [25]:

1. Problem setting: Setting goals that must be achieved in desirable futures from several aspects, e.g., economic and environmental performances.
2. Constructing logic trees: Supporting backward thinking in terms of causal relationships, where various ideas are generated by brainstorming among participants involved.
3. Describing storylines: Determining the basic structure of sub-scenarios, each of which is deployed from a key factor.
4. Describing sub-scenarios: Detailing and parameterizing sub-scenarios, after which each sub-scenario is evaluated using simulation models.

4. Case study: scenarios of SMI in Japan to 2050

In this section, we carried out a case study of the backcasting scenario method (see Section 3.2) using 3S Simulator. Note that we described and assessed scenarios of Japan’s SMI by deploying the scenario storylines presented in previous research [26]. Each step of the scenario design process is explained below.

4.1. Problem setting

The purpose of this scenario exercise was to describe scenarios of Japan’s sustainable manufacturing industry (SMI) to 2050. The authors organized two scenario workshops inviting approximately 10 researchers mainly from engineering, aiming to gain a good amount of ideas and knowledge regarding present and future manufacturing. The participants in the scenario workshops set three goals of SMI as (i) keeping the GDP proportion of the manufacturing industry to the entire industries in 2050 at the current level (19.3%) or more, (ii) keeping the proportion of employment from the manufacturing industry to the Japan’s population in productive age (15-64 years old) in 2050 at the current level (12.6%) or more, and (iii) the CO₂ emissions from the manufacturing industry in 2050 being 80% lower than the 1990 level.

4.2. Constructing logic trees

Based on the participants’ ideas, we constructed logic trees to achieve the three goals. Fig. 3 depicts a part of the developed logic tree. The resulting four branches were deployed to sub-scenarios.

Fig. 2. Example of using logic trees to support backward thinking.
4.3. Describing scenario storylines

Table 1 shows four scenario storylines (A-1, A-2, B-1, and B-2) of Japan’s SMI, which were developed based on the logic tree. Scenarios A and B differ in targeted markets; namely, Scenarios A and B focus mainly on the domestic and global markets, respectively. In Scenarios A (i.e., Sub-scenarios A-1 and A-2), product development policies align with the unique needs of Japanese consumers, such as Japanese cultures and special preferences. These products are named Galapagos products after Galapagos Islands, in which many unique species live. Sub-scenario A-1, however, looks at the global market in the long term, where Galapagos products are assumed to be finally accepted by consumers in the global market. In Sub-scenario A-2, products are sold only in the domestic market, where necessary materials and energy are supplied within the country (see Fig. 3). Sub-scenarios B-1 and B-2 are differentiated in how products and services are developed in the global market. Sub-scenario B-1 pursues local-oriented manufacturing systems, while Sub-scenario B-2 pursues products of high quality by drawing on Japanese high technologies.

4.4. Describing sub-scenarios

After putting together the ideas into several sub-scenarios, we assessed the sub-scenarios in order to test if each sub-scenario meets the predetermined goals (i)-(iii) in Section 4.1. For this purpose, we estimated economic and environmental performances of the scenario using the simulation tool that was developed based on input-output (IO) tables [26]. Fig. 4 describes the results of the four sub-scenarios in 2050. Sub-scenario A-2, which focuses solely on the Japanese market, is unsustainable in terms of GDP and employment as the domestic market shrinks due to a population decrease in Japan. The other three sub-scenarios have larger GDP than

![Diagram](image-url)

Fig. 3. Constructing a logic tree to develop the scenario (not exhaustive).

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Storylines</th>
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<tbody>
<tr>
<td><strong>A. Galapagos scenarios</strong></td>
<td></td>
</tr>
<tr>
<td><strong>A-1. Global Galapagos</strong></td>
<td>The Japanese manufacturing industry (JMI) produces “Galapagos” products, which mean products based on the special domestic demand. In the short term, the JMI produces Galapagos products for domestic markets. In the medium term, the JMI and the Japanese government cultivates the global market for Galapagos products by promoting Japanese culture, setting technological standards, and so on. The JMI enhances the Galapagos products for the global market. In the long term, the JMI exports Galapagos products to the cultivated global market.</td>
</tr>
<tr>
<td><strong>A-2. Japanese Galapagos</strong></td>
<td>The JMI concentrates on the domestic market. First, as in sub-scenario A-1, the JMI starts to develop Galapagos products for the domestic markets. The JMI refuses or fails to cultivate the global market. The JMI finds and nurtures potential domestic needs. Japanese consumers have unique demands for products, so foreign products are not accepted in the Japanese market. As a result, the JMI becomes dominant in Japan. In the long term, the JMI realizes balanced contraction with shrinking domestic markets.</td>
</tr>
<tr>
<td><strong>B. Global scenarios</strong></td>
<td></td>
</tr>
<tr>
<td><strong>B-1. Portfolio strategy</strong></td>
<td>The JMI develops a global business portfolio. It realizes on-site production all over the world and wins the global mass market. For this, the JMI dispatches Japanese employees to all parts of the world and investigates local demands. The JMI develops low energy consumption technology and material technology in parent factories in Japan. These technologies are advantages of the JMI under resource depletion. The domestic market is a part of the global market. Therefore, the domestic division develops and sells products locally.</td>
</tr>
<tr>
<td><strong>B-2. Japan quality pursuit</strong></td>
<td>The JMI develops special products for global niche markets in which high quality and reliability are required. Individual companies explore niche markets using their high technology, and the markets become oligopolies. The JMI will become service-oriented to realize high quality and reliability. The JMI constructs alliances of small- and medium-sized enterprises to explore global niche markets. Small oligopolistic business advances against a backdrop of resource depletion.</td>
</tr>
</tbody>
</table>

2010 as they earn money in the global market. However, the employment in Sub-scenario B-1 is relatively lower because it pursues on-site production outside Japan. None of the sub-scenarios achieves the CO2 reduction goal because the described scenario does not assume the mass introduction of low-carbon technologies (e.g., renewables and energy-saving
Regarding a), the usage of 3S Simulator was helpful for the logic tree in Fig. 3 visualized the cause-effect chains that CO2 reduction goal remains a future issue to be addressed.

5. Advantages and challenges of scenario design toward SMIs

In this section, we discuss advantages and challenges toward achieving SMIs based on the case study results.

5.1. Advantages

Designing scenarios is useful for sharing ideas and knowledge with different stakeholders in the form of narrative stories as described in Table 1. Based on the case study, we confirmed that scenarios’ values include clarifying assumptions, ideas, and logic to assume futures. That is, one characteristic of a scenario design approach was the combination of narrative stories and quantitative simulations. What is differentiated from simulations was that narrative storylines enabled an explicit representation of rationales for the mathematical model. For example, the rationale for the low employment rate in Sub-scenario B1 (result) was expressed as the transfer of the Japanese manufacturing industry to outside Japan (on-site production).

Moreover, given integrating a participatory approach into scenario design, we identified the following two advantages:

a) To help share and deepen an understanding of SMIs among the participants. Since scenarios are described as narrative stories, which include assumptions and simulation results, the participants (which may include experts and lay stakeholders) are able to easily share the story connecting the future and the present.

b) To help create a variety of visions of SMIs. While such visions are inherently normative and diversified, taking a participatory approach would lead to delineating creative futures by reflecting not only expertise provided by experts but also various ideas, values, and experiences provided by the participants.

Regarding a), the usage of 3S Simulator was helpful for clarifying the logical structure of the scenarios. For example, the logic tree in Fig. 3 visualized the cause-effect chains that determine the overall structure of the scenarios. This visualization is particularly meaningful to check the internal consistency of the scenarios. This would be a key advantage of using 3S Simulator when we deal with a great amount of information. In our experience in the case study, we learned that the explicit representation of the scenarios facilitates understanding among the participants. Moreover, this enables to generate more diversified ideas regarding the scenarios. In order to assess the effect of using 3S Simulator in a more scientific manner, we need to conduct protocol analysis of the scenario design process. This is one of our future issues.

5.2. Challenges

From a methodological viewpoint, however, there are many challenges remaining in designing scenarios of SMIs. We summarize the following three challenges to be addressed.

First, although a participatory approach is promising to delineate visions of and pathways to SMIs, the procedure has not yet been formalized sufficiently. Since it is required to not only create visions, but also assess the feasibility of the visions, the integration of backcasting and forecasting approaches is appropriate [27]. For example, the feasibility of predetermined visions derived from a backcasting approach should be ensured, despite various future uncertainties that might happen between now and the future end-point. A backcasting approach is useful to envision sustainable futures, while a forecasting approach is useful to analyze initial conditions and drivers of change.

The second challenge is to develop computer-aided scenario design systems to support a participatory approach and enhance collaborative work involving experts and stakeholders. One example is 3S Simulator [21], which provides an integrated platform to explicitly visualize the logical structure of scenarios so that participants can share a common understanding. Another example is Arizona State University’s Decision Theater [28], which helps visualize the participants’ opinions and differences. However, research on supporting participatory scenario design with computational assistance has not yet been widely explored.

The third challenge is how to resolve inequity between current and future generations. Since intergenerational inequity is a key aspect of sustainability issues in general, reflecting the voice of future generations on scenario design is a prerequisite to delineate visions of SMIs. To this end, one approach is to virtually create future generations [29], thereby enabling a dialog between current and future generations through participatory scenario design.

6. Conclusions

In this paper, we introduced the concept of scenario design as an emerging research field in the CIRP community in order to accelerate research on sustainable manufacturing industries (SMIs). We discussed the possibilities and research challenges of scenario design toward SMIs based on the literature review and the scenario exercise of Japan’s SMI to 2050. We summarized the research challenges to be tackled in...
the following three points – (1) developing scenario design procedures by integrating forecasting and backcasting, (2) developing computer-aided systems to assist participatory design of scenarios, and (3) incorporating the voice of future generations in scenario design.

References
